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Survivability, Structures, and Materials Directorate

Technical Report

Feasibility Demonstration of a Pulsed Acoustic Device for Inhibition of Biofouling in Seawater Piping

by

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This report describes a preliminary field test of a new biofouling control device designed for seawater piping and cooling systems. This technology uses a pulsed, underwater electrical discharge to generate an acoustic wave in pipes. The test was conducted during February 1994 in a seawater test loop, constructed of clear PVC piping, located at the Naval Surface Warfare Centers' Corrosion Test Facility in Dania, Florida. It included an untreated, control pipe and another identical pipe which was treated with an acoustic pulse every two seconds, ten hours per day, for 10 days. Results of visual observations, microbial counts, environmental electron microscopy (ESEM) and energy-dispersive x-ray analysis (EDS) demonstrated a significant reduction in the rate of biofouling in the pipe treated with the pulsed acoustic device compared to the control.

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Contents

Figures

Tables

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The work described in this report was performed by the Applied Materials Sciences Department (Code 68) of the Survivability, Structures and Materials Directorate at the Naval Surface Warfare Center, Carderock Division (NSWCCD) and by the Pulsed Power Systems and Technology Group of the Systems Research and Technology Department (Code B20) at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD). The experimental work was funded by the Naval Surface Warfare Center, Dahlgren Division Seed and Venture Program. Preparation of this Technical Report was funded by the Office of Naval Research, Code 334 as part of the "Advanced Heat Removal Concepts for Handling Large Thermal Transients in Shipboard Power Systems" Task of the FY 1998 6.2 Power and Automation Systems Program (Program Element 62121N), and the Office of Naval Research, Code 331 as part of the FY 1998 6.2 Environmental Quality Applied Research Program (Program Element 62121N).

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Executive Summary

This report describes a preliminary field test of a new biofouling control device designed for seawater piping and cooling systems. This technology uses a pulsed, underwater electrical discharge to generate an acoustic wave in pipes. The test was conducted during February 1994 in a seawater test loop, constructed of clear PVC piping, located at the Naval Surface Warfare Centers' Corrosion Test Facility in Dania, Florida. It included an untreated, control pipe and another identical pipe which was treated with an acoustic pulse every two seconds, ten hours per day, for 10 days. Results of visual observations, microbial counts, environmental electron microscopy (ESEM) and energy-dispersive x-ray analysis (EDS) demonstrated a significant reduction in the rate of biofouling in the pipe treated with the pulsed acoustic device compared to the control.

Introduction

Virtually all surfaces exposed to seawater for any period of time are susceptible to fouling by communities of marine microorganisms, algae and invertebrates. Biofouling of marine structures and vessels has long been a concern both to the Navy and to industries and public utilities that operate vessels or engineering systems at or in the sea. The practical consequences of fouling, in terms of both economic losses and operational problems and downtime, are considerable. Biofouling increases the frictional resistance of ship hulls and propellers, leading to increased fuel consumption, loss of speed, and additional noise and engine stress [Characklis, W. G., N. Zelver, and M. Turakhia, 1984; Haderlie, E. C., 1984]. Journey times increase, and frequent dry-docking is required to remove fouling and renew antifouling coatings. In seawater cooling systems biofilms can lead to losses due to impairment of heat transfer efficiency [Aftring, R. P., and B. Taylor, 1979]. Pipes, filters and strainers may become partially or completely obstructed. Corrosion due to biological activity on fouled surfaces may lead to premature failure of materials [Jones, J. M., and B. J. Little, 1990].

Modern solutions to the biofouling problem have included biocide injection, new types of fouling resistant coatings and materials, electrochemical chlorination, electromagnetic methods and mechanical removal techniques [Fischer, E. C., 1984]. These and other biofouling control methods have been reviewed and evaluated in a previous report [Walch, M., and R. A. Brizzolara., 1998].

Chlorination and mechanical approaches, until recently, have been among the methods of choice for controlling biofouling in piping and heat exchanger systems. Mechanical cleaning is labor intensive and often requires that ship systems be taken offline for a period of time. Chlorination is a relatively inexpensive and effective biofouling control strategy. Environmental concerns and increasingly stringent discharge regulations, however, are continually requiring users of chemical biocides to consider or use other methods. Even though development of dechlorination technologies [Christian, D.K., J.O. Bergh and E.D. Thomas., 1995] and new strategies for chlorine minimization [Weber, B.E. and D.A. Brown., 1997; Jenner, H.A., and H.J.G. Polman., 1993] may allow chlorine use by the Navy to continue for some period of time, discharge limits for chlorine and other chemicals continually decrease and may eventually reach zero. Hence, alternatives to chlorination for biofouling control in ship systems are being sought.

This report describes a preliminary field test of one such alternative system, which was developed at the Naval Surface Warfare System (Dahlgren and Carderock Divisions). This technology uses a pulsed, underwater electrical discharge to generate an acoustic shock wave in pipes. The field test was conducted at the Naval Surface Warfare Center's Corrosion Test Facility in Dania, Florida, using seawater pumped from the Port Everglades shipping channel through plastic piping. Results demonstrated a significant reduction in the rate of biofouling over a 10-day period compared to an untreated control pipe.

Details of the device design, experimental protocols and results are described below.

Experimental Protocols

Test Site

The field test was performed at the NSWCCD Marine Corrosion Test Facility in Dania, Florida from 19 February to 27 February 1994. The facility is located on the south side of the Port Everglades shipping channel, at its opening to the Atlantic Ocean. The test loop was constructed on a concrete pad next to the channel. Water for tests conducted at this site is drawn directly from the shipping channel into an elevated 1500-gallon holding tank using a 10-HP pump. From there it is pumped to the tests.

Test Loop Design

A diagram of the test loop configuration is shown in Figure 1. Seawater from the 1500-gallon plastic holding tank was fed to a manifold leading to two identical pumps. From here, the water was pumped through parallel lines of 2-inch diameter, schedule 40 PVC pipe. Pipes in the last 40-foot leg of the loop were made of clear PVC so that fouling could easily be seen. Ball valves on the lines controlled flow rate, which was set to 7 gpm, or 0.5 ft/sec. Flow was measured both by bucket and stopwatch and by a Controlotron flow meter.

The acoustic source (spark gap) was inserted through a port into one of the clear pipes at its center. Sampling ports were located 10 feet upstream from the source, 2 feet downstream, 10 feet downstream and 20 feet downstream. Sampling ports also were placed in the same positions on the control leg, which received no acoustic treatment. The pipes were mounted on low wooden supports and were isolated acoustically from one another by cushioning them with thick foam. Acoustic isolation was confirmed using pressure transducers coupled to an oscilloscope.

Pulsed Acoustic Treatment

The hardware used in generating pulsed underwater shock waves in this field test is described in United States Patent No. 5,636,180. A copy of the patent is included in this report as Appendix A. Acoustic shock waves were generated by applying short-duration, high-voltage electrical pulses across a spark gap inserted into and fully immersed in the pipe lumen. The electrical discharges were produced by high voltage pulses (12-15 kV) from a storage capacitor. The rise time of the current between the electrodes was less than 1 microsecond. The resulting acoustical shock waves generated at the electrodes interact with biofouling organisms to prevent attachment to adjacent surfaces.

Seawater flow through the test loop and operation of the pulsed acoustic source began on the morning of 19 February. The treatment was run for an average of 10 hours per day and was shut down at night, because the system was not designed to run unattended. Average power use was 25 W, or 4 W per square foot treated. The repetition rate of the acoustic pulse was 0.5 Hz (once every two seconds).

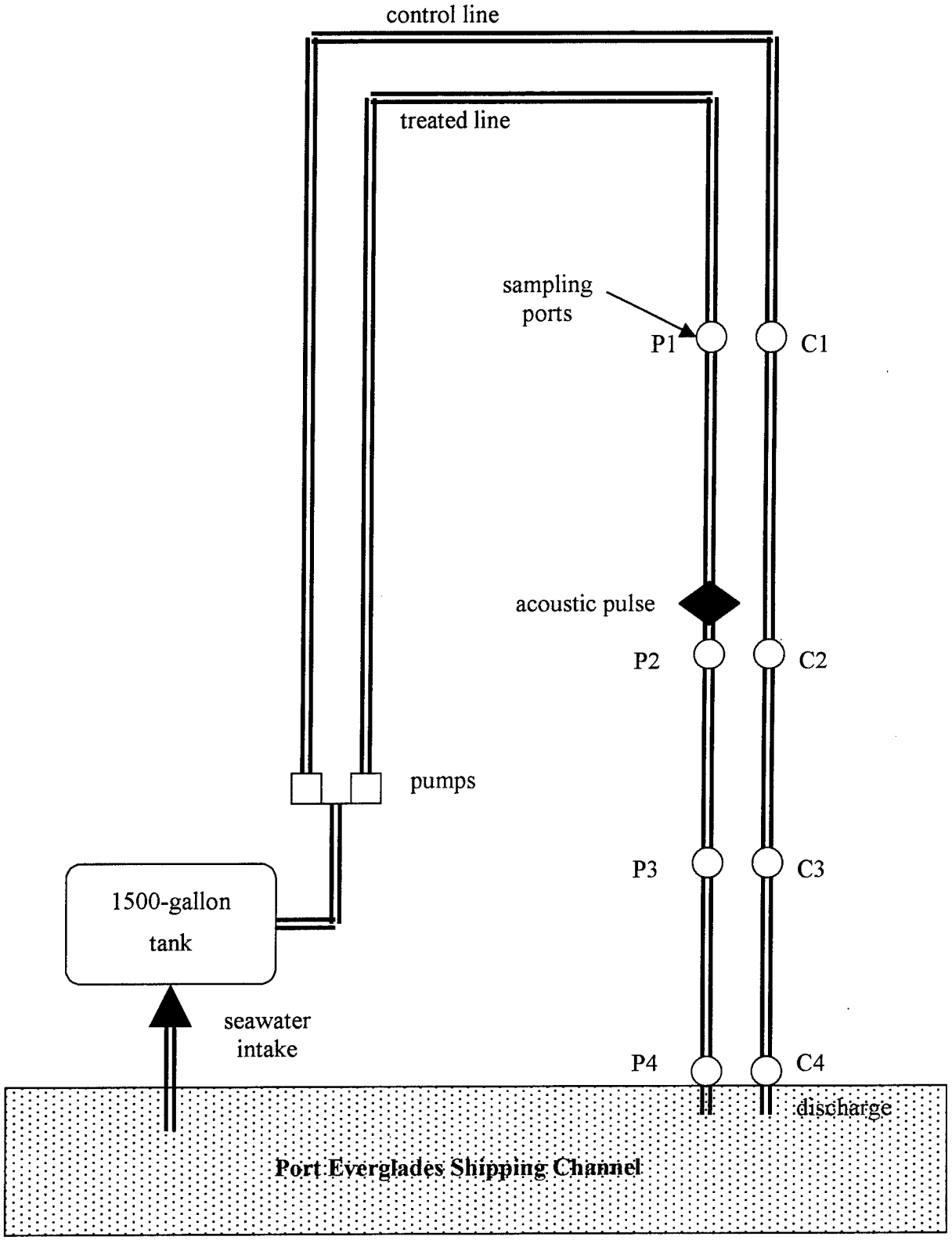


Figure 1. Configuration of seawater test loop, consisting of parallel PVC pipes, one control ("C") and one treated with acoustic pulses ("P").

Analyses of Biofouling

Visual observations of pipe fouling

The clear legs of test loop were examined visually on 24 February and 27 February, i.e., six and nine days into the test. Observations of fouling were recorded by photographing sections of the control and treated piping runs against a white background at distances 1, 5, 15 and 25 feet downstream of the location of the acoustic source, and at 5 and 15 feet upstream of it.

Microbial counts from pipe walls

Periodically during the test, the sampling ports were opened, and the pipe walls at those points were scraped with sterile cotton swabs for bacterial counts. Each sample was taken by making 15, 2-inch swipes with even pressure against the pipe wall. The intent was not to remove all cells from an area, but rather to obtain samples of the biofilm communities in a standardized way so that they could be compared. Scrapings were taken on the sides of the pipes to avoid sediment in the bottom area as well as intermittently dried areas at the top. Care was taken to avoid swabbing the same place on the pipe wall more than once.

After scraping the swabs were shaken vigorously into sterile culture tubes containing 2.0 ml filtered (0.2 μ pore size) seawater. The resulting suspension of cells was serially diluted and spread plated onto Marine Agar 2216 (Difco). Samples of seawater from the control and treated pipes also were counted. The plates were incubated at room temperature and counted 2 to 3 days later.

Presence/absence tests for general anaerobes, sulfate-reducing bacteria and acid-producing bacteria also were performed by inoculating the undiluted suspensions of bacteria into vials of broth prepared for these purposes by BioIndustrial Technologies (Arlington, Texas). 0.5 ml of the scrapings suspensions and 1.0 ml of the water samples were used as inocula. These vials were incubated at room temperature for up to one week before scoring positive or negative for growth of the corresponding type of bacteria.

Analysis of nylon coupons

One-inch diameter nylon washers were used as coupons to monitor microbial biofouling in the test loop during the test. Nylon was chosen because of its similarity to the PVC piping material. For each sampling port, four washers were mounted on a short threaded Teflon rod, separated by nylon spacers. The threaded rod was inserted into a cylindrical plastic plug machined to fit tightly into the hole at each port. When inserted into the port, the stack of coupons projected into the center of the pipe lumen, with the flat surfaces of the coupons oriented parallel to the direction of water flow.

Coupons were removed from the sampling ports on days 3, 6 and 9 of the test. They were handled with clean forceps and immediately placed into plastic tubes containing 0.18% formaldehyde in filtered seawater (0.2 μ pore size). Samples were refrigerated until analysis.

Coupons pulled on 21 and 24 February (days 3 and 6) were examined with an Electroscan E3 environmental scanning electron microscope (ESEM) located at the test site. Accelerating voltage was 14-16 kV, working distance 6-7 mm, and water vapor pressure 5-6 Torr. Coupons

pulled on 27 February (day 9) were sent to the Naval Research Laboratory Detachment, Stennis Space Center, Mississippi. There they were similarly examined by ESEM. Energy-dispersive x-ray analysis (EDS) also was performed on the samples to obtain elemental spectra of the coupon surfaces.

Results

Most of the visible fouling was due to brownish-green filamentous algae, which were exposed to sunlight in the clear pipes. No invertebrates were observed.

At the conclusion of the test, the control leg of the test loop was moderately fouled along its entire length. Fouling was heaviest on the bottoms and lower sides of the pipe. Fouling in the treated pipe was similar to the control downstream of sampling port P3 (Figures 3b, 3c, 5c, 5d) and slightly less fouled between ports P2 and P3 (Figures 3a, 5b) and upstream of port P1 (Figure 4c). The treated pipe was extremely clean for 6-8 inches between the acoustic source and P2, apparently due to reflection of the acoustic wave when it hit the dissimilar material in the port (Figures 2, 4a). The upstream leg of the treated pipe was cleaner than the control pipe all the way up to P1 (Figures 4a, 4b).

Fouling in general in the treated pipe was slower, with longer lag time than the control. The differences in extent of fouling between the treated pipe and the control became less pronounced with time. It is likely that much of the fouling in the treated leg was initiated at night when the acoustic source was turned off. Once fouling is initiated, low-energy pulsed acoustics may not remove adhered organisms from the surface.

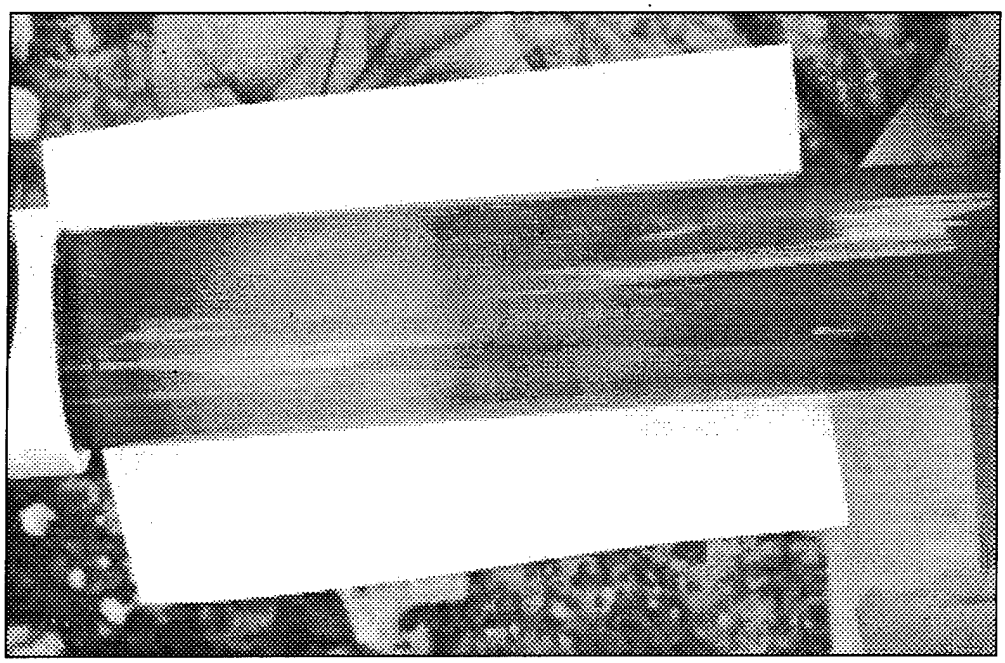
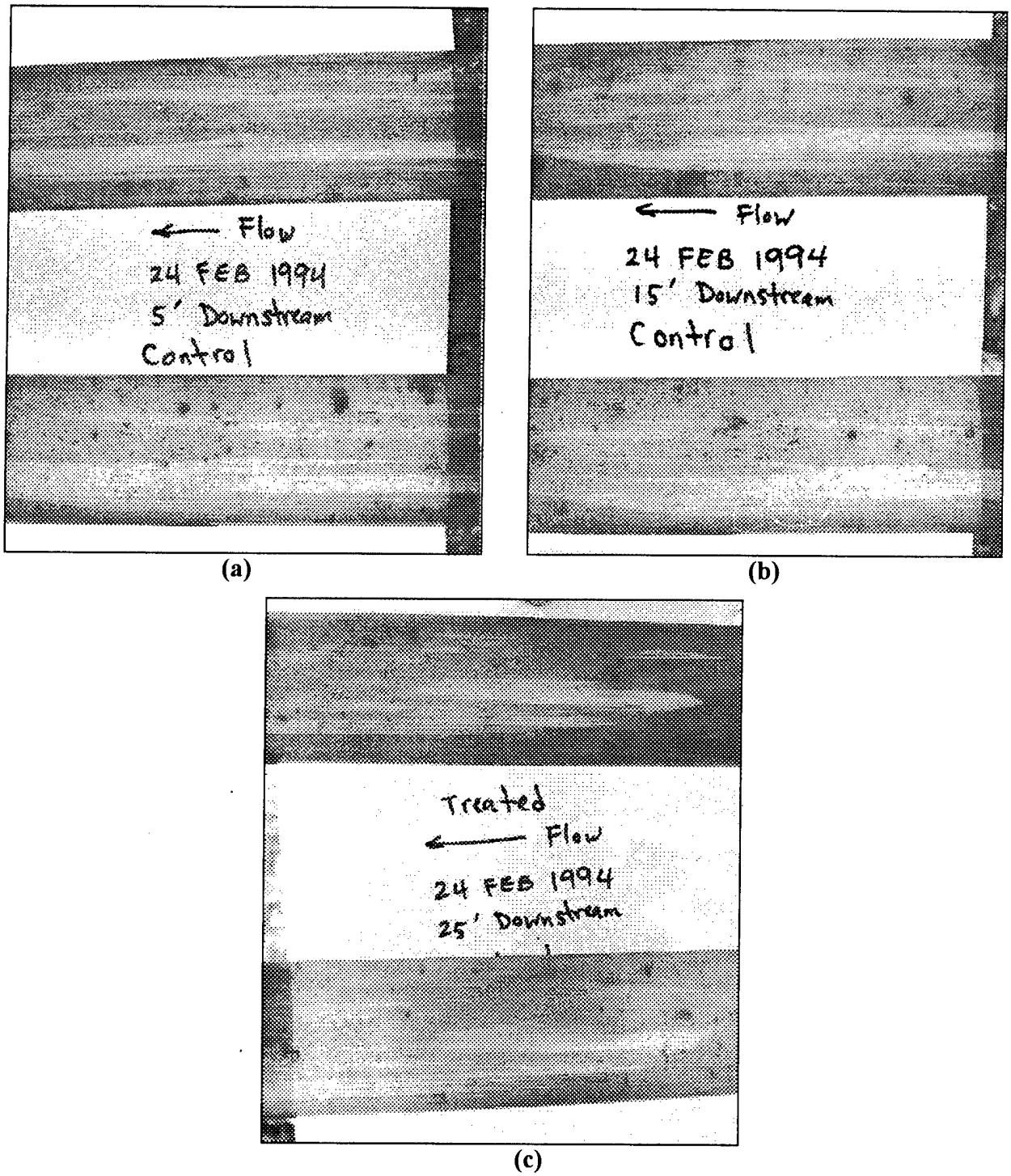
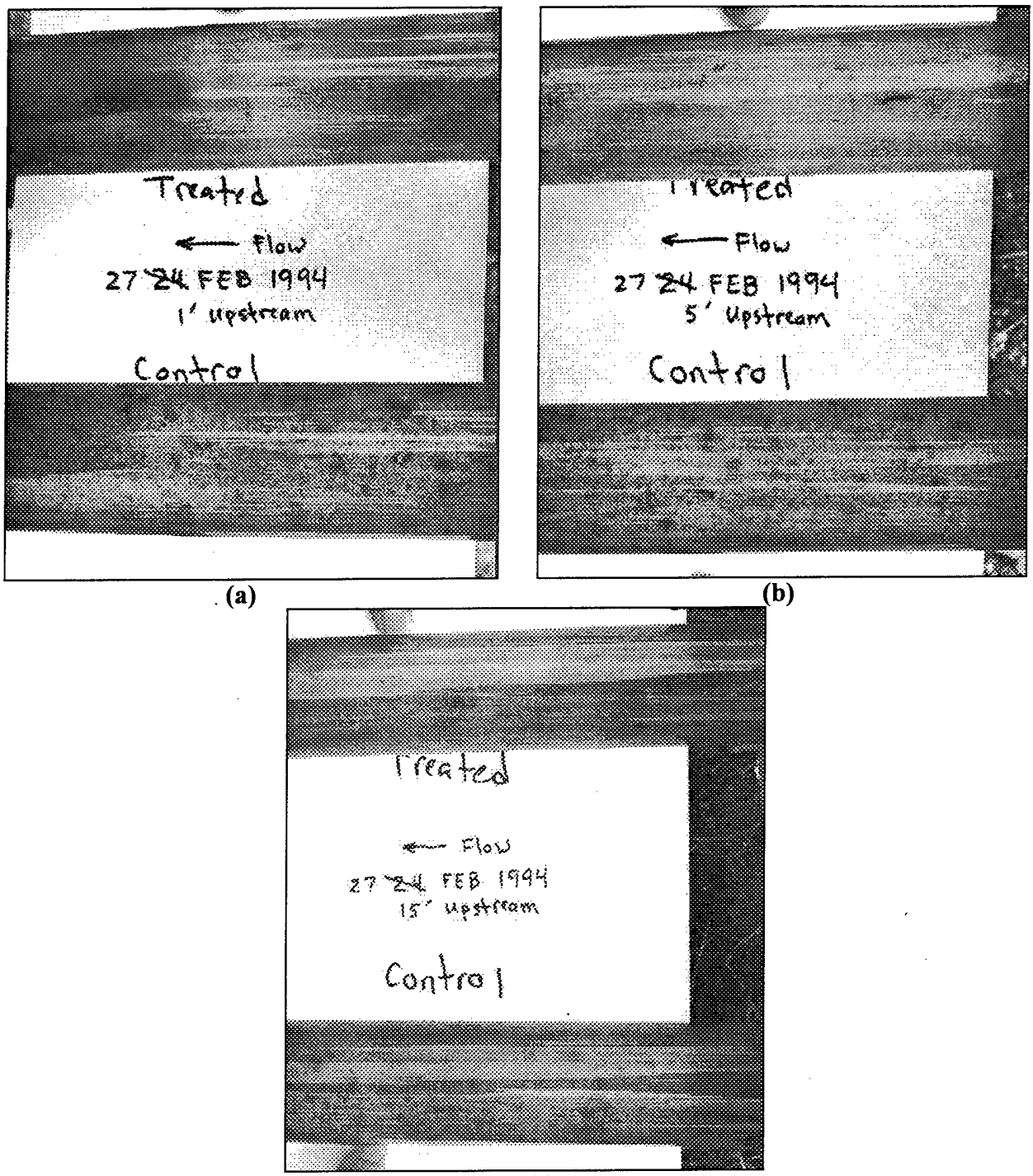


Figure 2. Particularly clean region of treated pipe next to a pipe union and sampling port, where the acoustic wave was reflected back on itself.



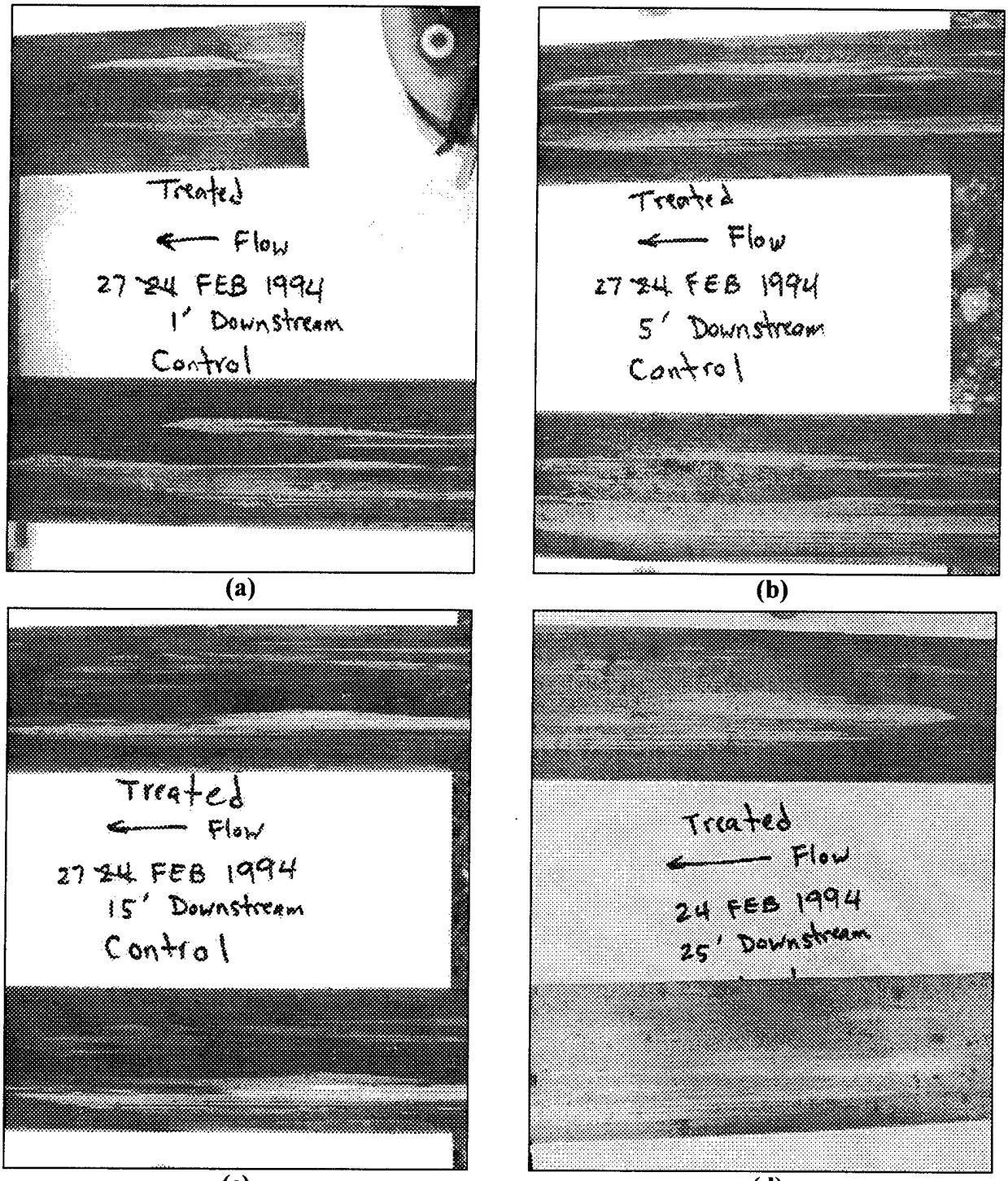
Treated pipe is at the top of each photograph, control at the bottom. Arrows indicate the direction of water flow. "Downstream" and "upstream" labels are in reference to the location of the pulsed acoustic source.

Figure 3. Photographs of biofouling accumulated in control and treated legs of the test loop on 24 February (day 6).



Treated pipe is at the top of each photograph, control at the bottom. Arrows indicate the direction of water flow. "Upstream" labels are in reference to the location of the pulsed acoustic source.

Figure 4. Photographs of biofouling accumulated in control and treated legs of the test loop on 27 February (day 9).



Treated pipe is at the top of each photograph, control at the bottom. Arrows indicate the direction of water flow. "Downstream" labels are in reference to the location of the pulsed acoustic source.

Figure 5. Photographs of biofouling accumulated in control and treated legs of the test loop on 27 February (day 9).

Results of viable plate counts of bacteria scraped from the walls of both pipes, in general, supported our visual observations of the fouling. Through the sixth day of the test, counts of samples taken from ports P1 and P2 of the treated pipe were up to an order of magnitude lower than those of samples from the corresponding ports in the control pipe (Table 1). These are the two ports closest to the acoustic source on the upstream and downstream sides, respectively. No replicates were done, so we do not know whether this difference is statistically significant. By the ninth day these differences had begun to disappear, again indicating that bacteria were not removed by the acoustic waves once they had adhered to the pipe surfaces. Like the visual observations, the plate counts also demonstrated that the protective effects of the acoustic device did not extend far beyond the first sampling port encountered by the shock wave.

Presence/absence tests for general anaerobic bacteria, sulfate-reducing bacteria and acid-producing bacteria were performed because these groups of microorganisms often are associated with microbiologically-influenced corrosion (MIC) in seawater piping and cooling systems [Little, B. J., P. A. Wagner, W. G. Characklis, and W. Lee, 1990]. Results of these tests (Tables 2, 3, 4) show no significant differences between the control and treated pipes after the media vials had been incubated for one week. In general, however, we observed that positive reactions in vials inoculated from the treated pipe developed more slowly than those from the control. This may be a reflection of lower numbers of these microorganisms occurring in the treated part of the test loop. A quantitative test would be required to confirm this.

In general, visual observations also were supported by ESEM analysis. At sites viewed by ESEM, there usually was less biofouling on coupons from the treated pipe than on those from the control leg of the test loop (Figures 6-8). This difference was particularly noticeable at ports C1/P1 and C2/P2, which were located closest to the acoustic source (Figures 6, 8). As distance from the source increased and, in particular, as the number of intervening pipe fittings and other potential interferences with the acoustic wave increased, less difference was observed between the extent of fouling in the two pipes. Algal attachment and growth was substantially greater on the control coupons (Figures 6, 8, 10). Algae included filamentous forms, as well as diatoms. Fouling was patchy on all of the coupons, particularly those pulled from the treated pipe. This observation again supports the conclusion that the pulsed acoustics are able only to prevent attachment of microorganisms. Once attached, the organisms can continue to grow into large colonies or patches.

EDS spectra obtained from the coupons aided in identification of the fouling material. Spectra from relatively clean coupons, such as that from port P1, basically reflected the elements in seawater salts (Na, Mg, Cl, Ca), with prominent Ca peaks which may represent $CaCO_3$ deposition (Figure 9). Diatoms were abundant on many of the more heavily fouled surfaces, and EDS spectra from these coupons featured large Si peaks (Figure 10). Diatoms were most numerous in samples taken at the end of the test. Bacteria and filamentous algae predominated on coupons that were pulled earlier in the experiment. Some of the coupons had areas of brown staining. Large amounts of Fe, Cr and Ni confirmed that these stains were corrosion products, perhaps derived from the test loop pumps (Figure 11).

Table 1. Viable plate counts of bacteria obtained from water samples and from scrapings of the pipe walls.

Counts are in units of colony-forming units (cfu) per ml for water samples, and cfu per cm^2 for wall scrapings.

Sample	Microbial Counts (cfu per ml or per cm^2)		
	2/20/94 (Day 2)	**2/24/94 (Day 6)**	**2/27/94 (Day 9)**
Water sample, port C1	1.1×10^4		
Water sample, port C4	1.7×10^3		
Water sample, port P1	3.6×10^3		
Water sample, port P4	2.1×10^3		
Pipe Wall, C1	1.6×10^4	1.7×10^5	5.8×10^3
Pipe Wall, C2	2.1×10^4	3.3×10^4	1.6×10^4
Pipe Wall, C3	1.3×10^4	4.0×10^4	4.4×10^3
Pipe Wall, C4	1.7×10^3	1.1×10^4	1.4×10^3
Pipe Wall, P1	4.5×10^3	1.5×10^4	2.1×10^4
Pipe Wall, P2	2.1×10^3	1.0×10^4	7.5×10^3
Pipe Wall, P3	1.1×10^4	1.4×10^4	6.0×10^3
Pipe Wall, P4	9.6×10^2	8.6×10^3	2.2×10^4

Table 2. Results of presence/absence tests for general anaerobic bacteria for water samples from each pipe as well as for scrapings from the pipe walls.

"C" indicates sample came from the control pipe. "P" indicates sample came from the pipe treated with pulsed acoustics. The number indicates the location of each sampling port (refer to Figure 1).

Sample	2/20/94	2/24/94	2/27/94
Water sample, port C1	+		
Water sample, port C4	+		
Water sample, port P1	+		
Water sample, port P4	+		
Pipe Wall, C1	+	+	-
Pipe Wall, C2	+	+	+
Pipe Wall, C3	+	+	-
Pipe Wall, C4	+	-	
Pipe Wall, P1	+	-	-
Pipe Wall, P2	+	+	-
Pipe Wall, P3	+	-	+
Pipe Wall, P4	+/-	-	

Table 3. Results of presence/absence tests for sulfate-reducing bacteria for water samples from each pipe as well as for scrapings from the pipe walls.

"C" indicates sample came from the control pipe. "P" indicates sample came from the pipe treated with pulsed acoustics. The number indicates the location of each sampling port (refer to Figure 1).

Sample	2/20/94	2/24/94	2/27/94
Water sample, port C1	+		
Water sample, port C4	+		
Water sample, port P1	+		
Water sample, port P4	+		
Pipe Wall, C1	-	-	-
Pipe Wall, C2	+	-	-
Pipe Wall, C3	+	-	-
Pipe Wall, C4	-	-	-
Pipe Wall, P1	-	-	-
Pipe Wall, P2	-	-	-
Pipe Wall, P3	+	-	-
Pipe Wall, P4	+	-	-

Table 4. Results of presence/absence tests for acid-producing bacteria for water samples from each pipe as well as for scrapings from the pipe walls.

"C" indicates sample came from the control pipe. "P" indicates sample came from the pipe treated with pulsed acoustics. The number indicates the location of each sampling port (refer to Figure 1).

Sample	2/20/94	2/24/94	2/27/94
Water sample, port C1	+		
Water sample, port C4	+		
Water sample, port P1	+		
Water sample, port P4	+		
Pipe Wall, C1	+	-	+
Pipe Wall, C2	+	+	+
Pipe Wall, C3	+	+	+
Pipe Wall, C4	+	-	
Pipe Wall, P1	+	-	+
Pipe Wall, P2	+	+	+
Pipe Wall, P3	+	+	+
Pipe Wall, P4	+	-	

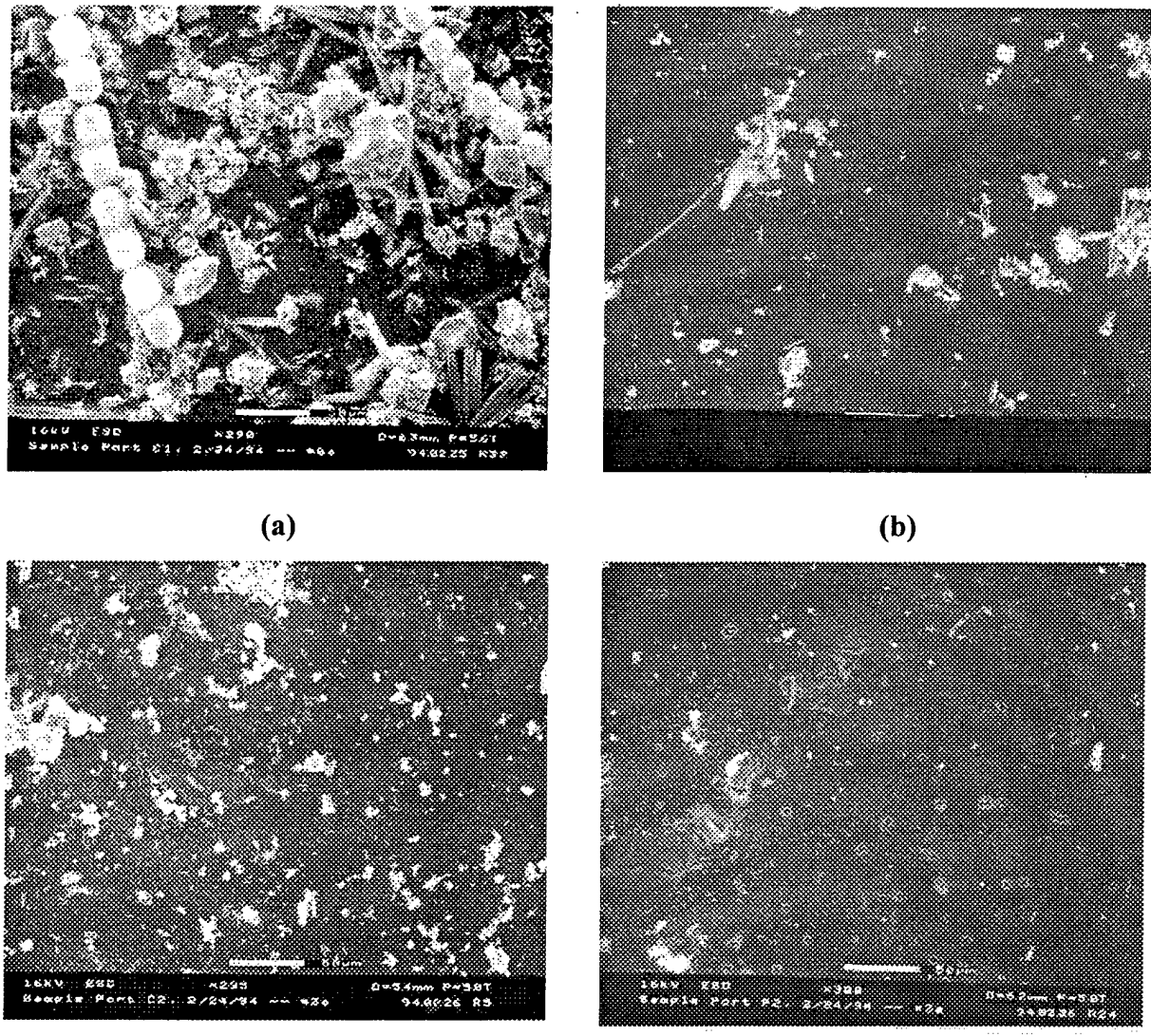


Figure 6. ESEM micrographs of coupons taken from sampling ports closest to the acoustic source on 24 February, Day 6 of the test: (a) C1 – control, 10 ft upstream; (b) P1 – treated, 10 ft upstream; (c) C2 – control, 2 ft downstream; (d) P2 – treated, 2 ft downstream. Magnification in micrographs is 300X. Size bar at bottom = 50 μm.

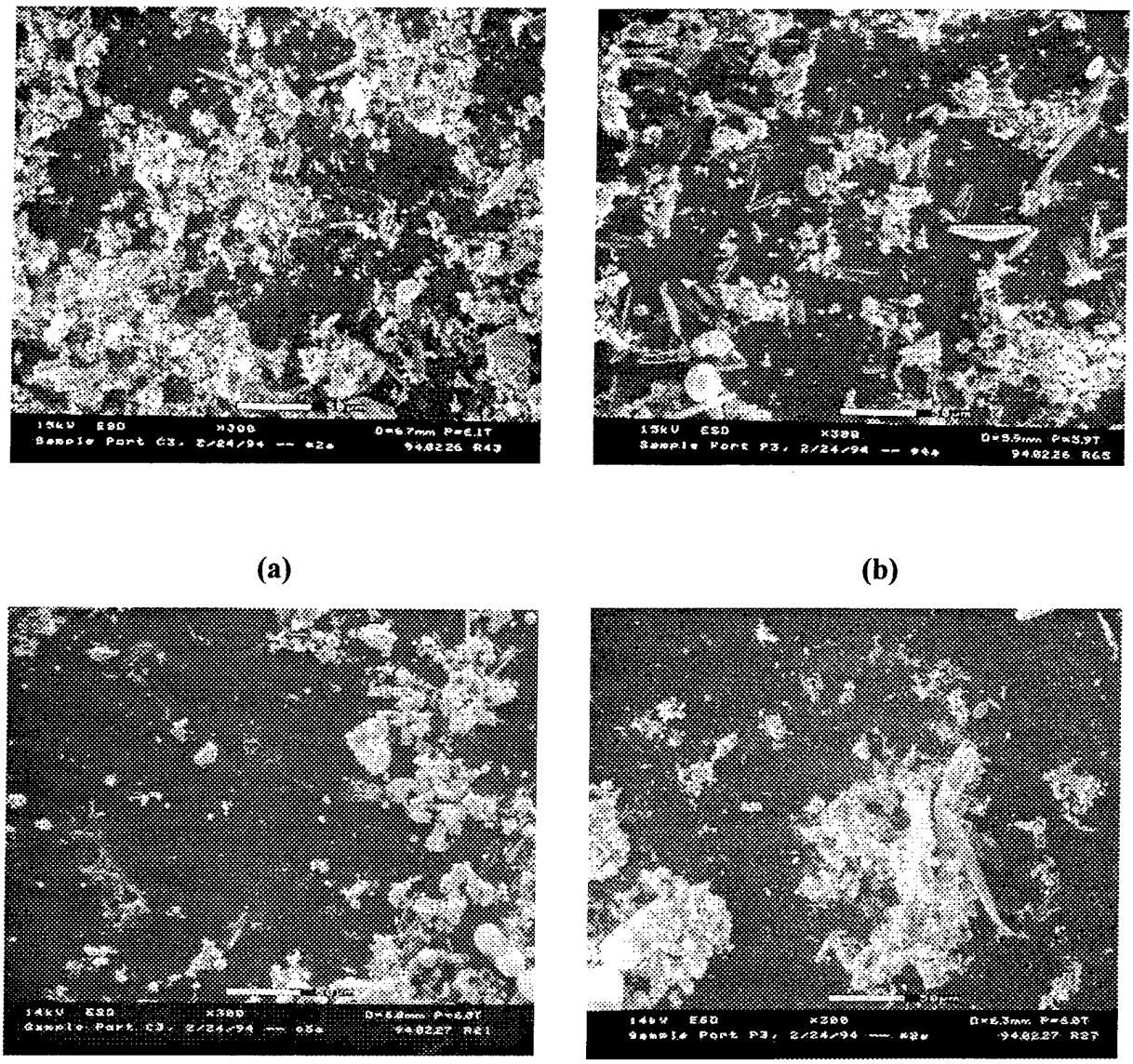


Figure 7. ESEM micrographs of coupons taken from sampling ports closest to the acoustic source on 24 February, Day 6 of the test: (a) C3 – control, 10 ft downstream; (b) P3 – treated, 10 ft downstream; (c) C4 – control, 20 ft downstream; (d) P4 – treated, 20 ft downstream. Magnification in micrographs is 300X. Size bar at bottom = 50 μm.

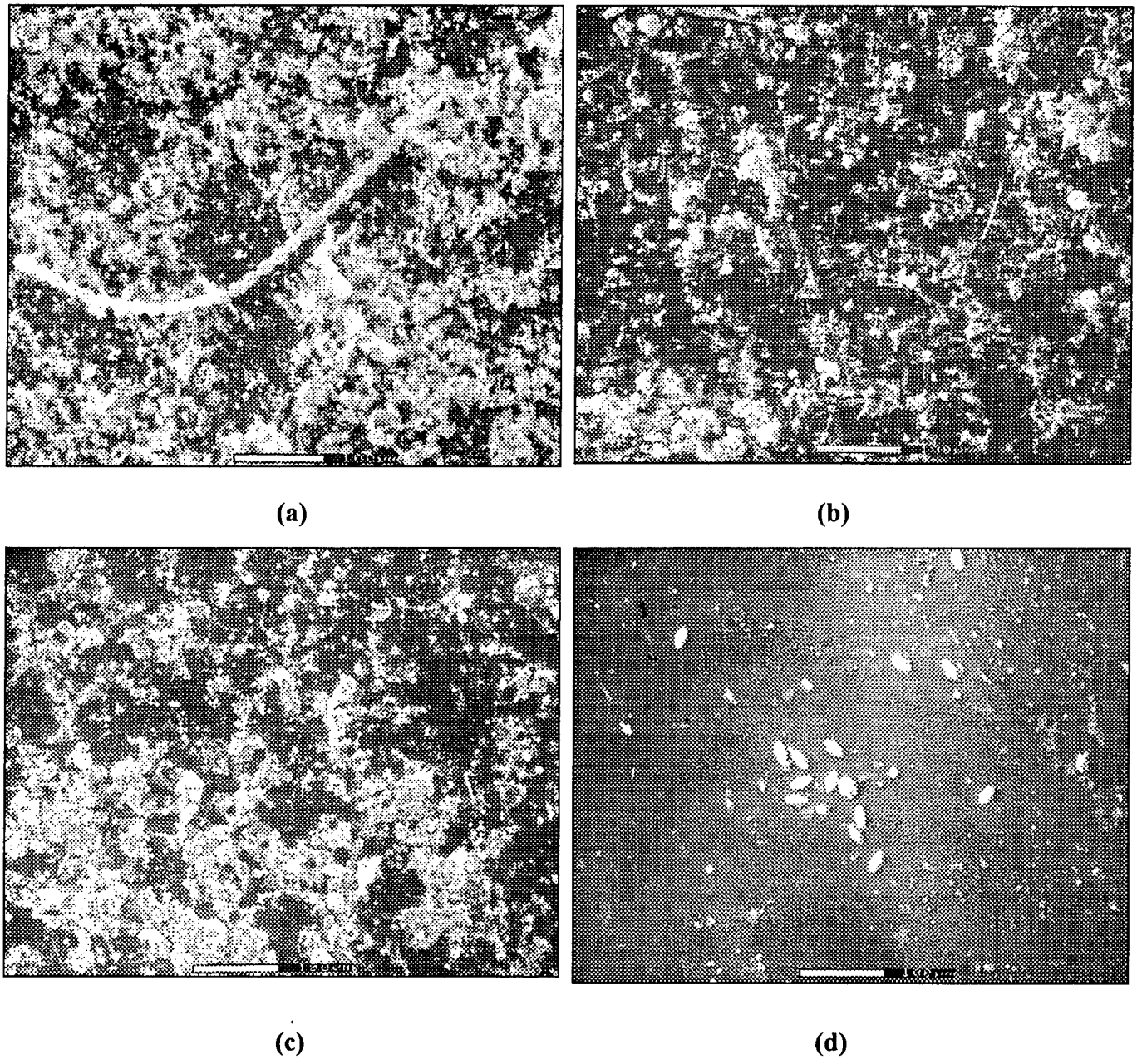
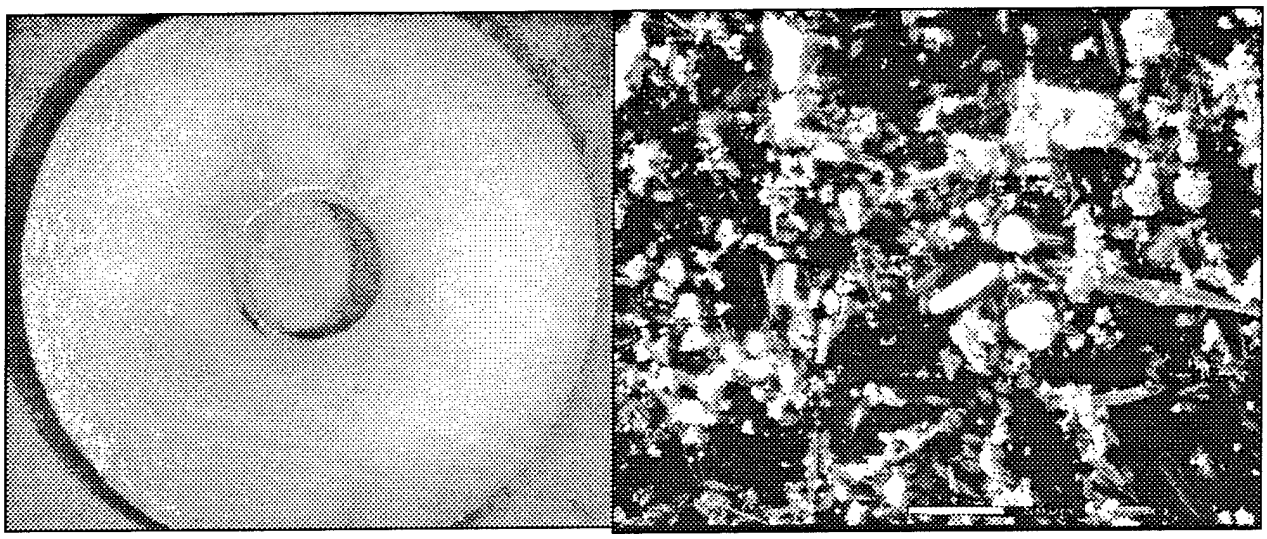
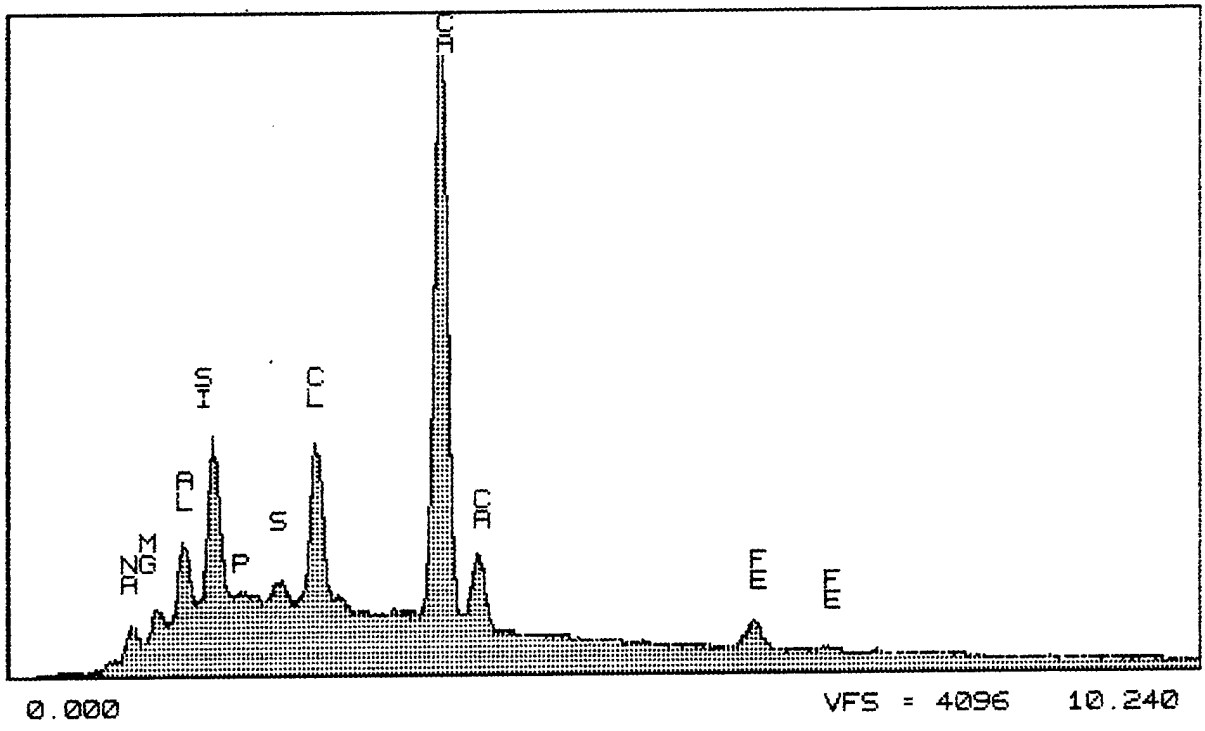


Figure 8. ESEM micrographs of coupons taken from sampling ports closest to the acoustic source on 27 February, Day 9 of the test: (a) C1 – control, 10 ft upstream; (b) P1 – treated, 10 ft upstream; (c) C2 – control, 2 ft downstream; (d) P2 – treated, 2 ft downstream. Magnification in micrographs is 150X. Size bar at bottom = 100 μm.

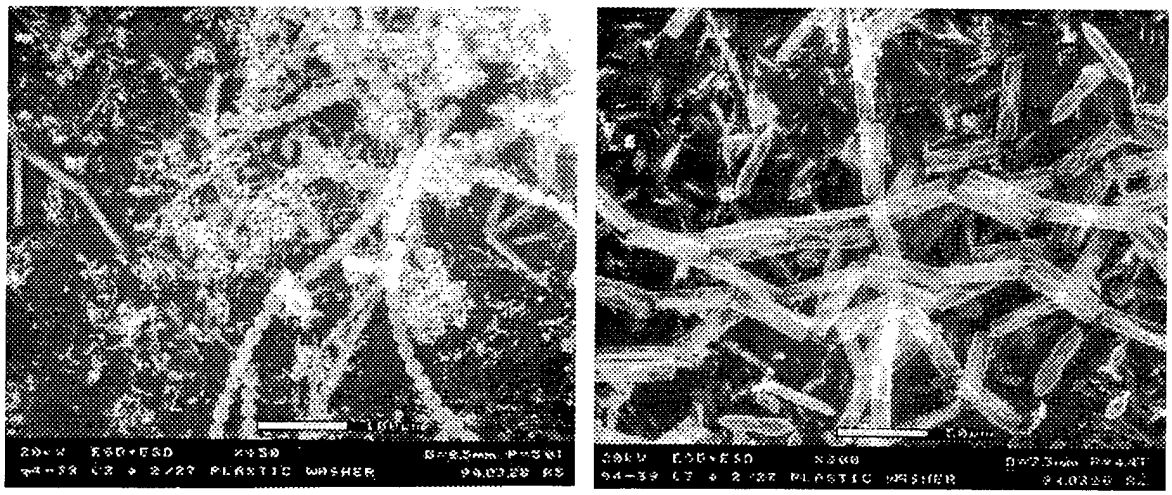


(a) (b)

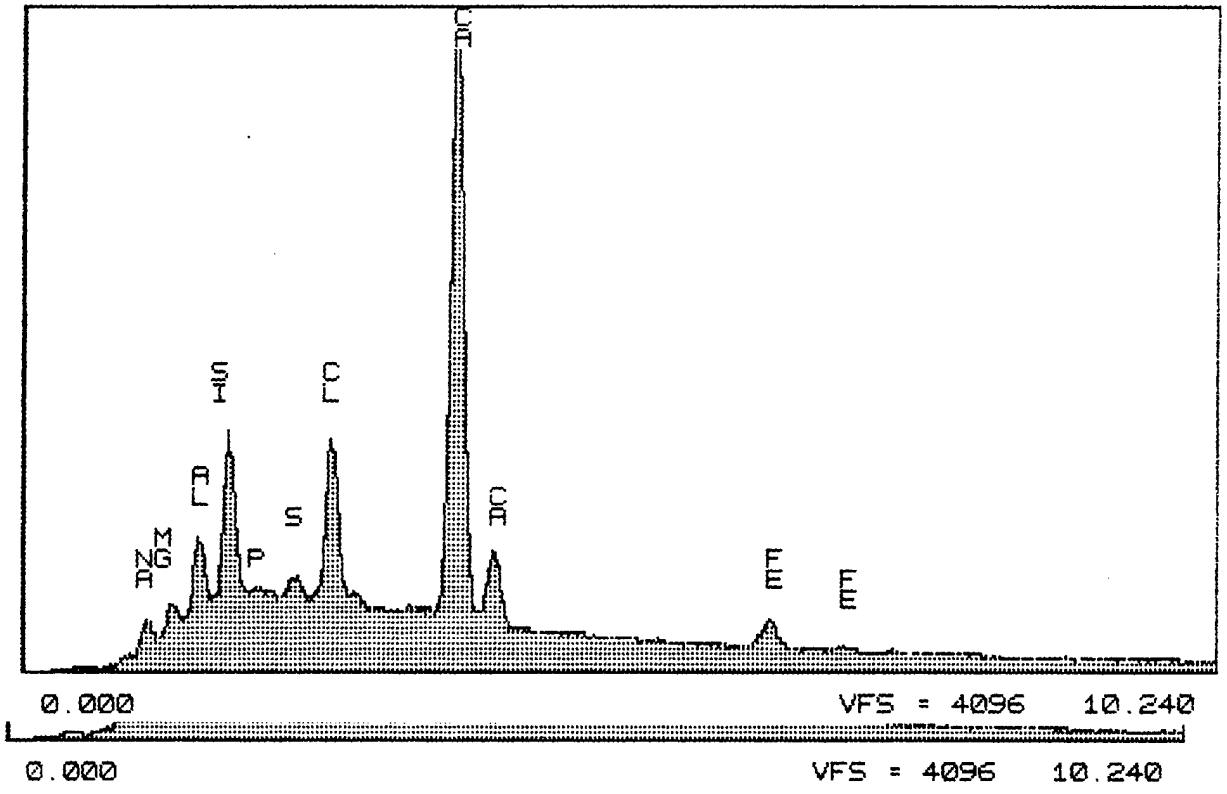


(c)

Figure 9. ESEM micrograph (b) and EDS spectrum (c) from coupon (a) pulled from sampling port P1 (treated pipe) on 27 February, Day 9 of the test. Magnification in micrograph is 300X. Size bar at bottom = 50 μm.

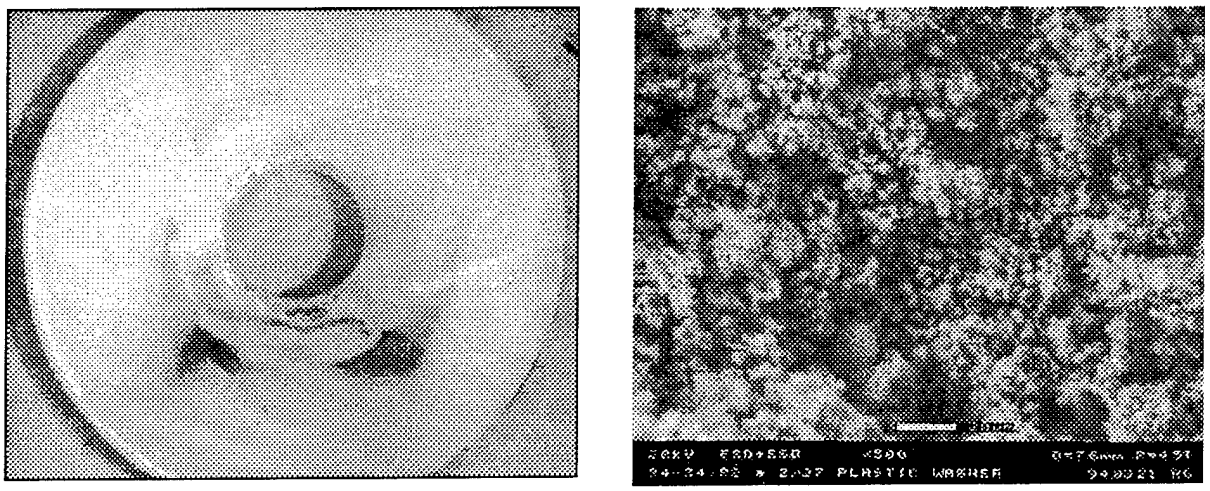


(a) (b)

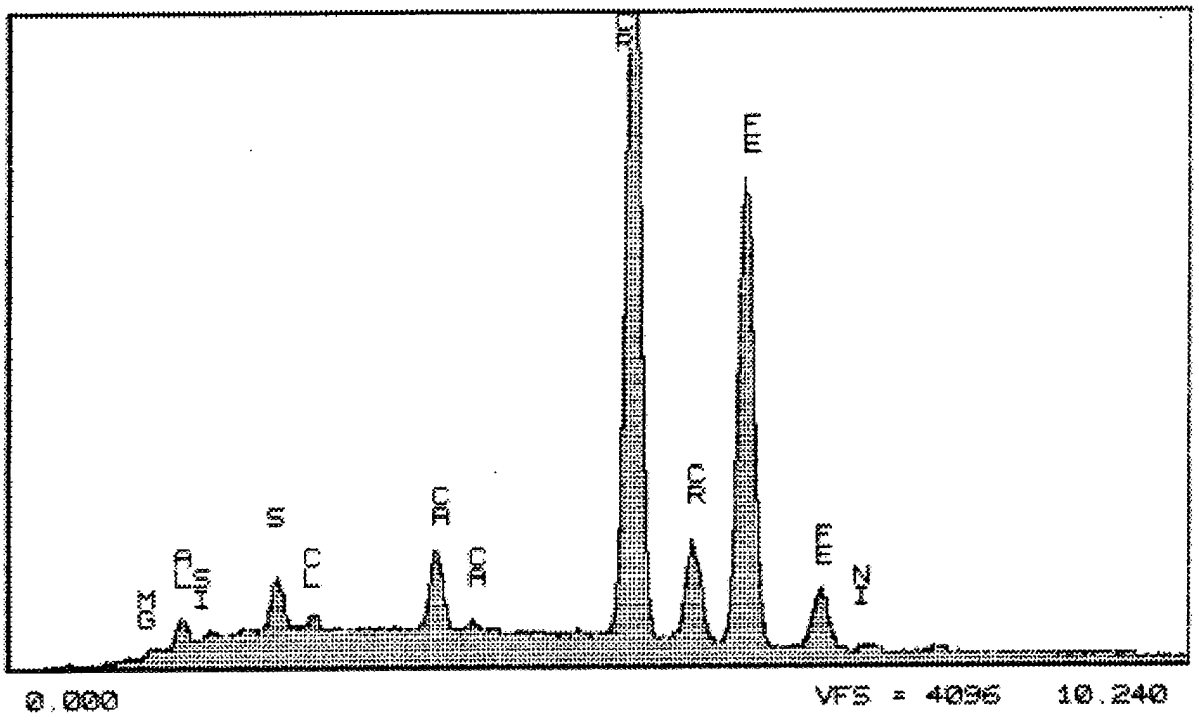


(c)

Figure 10. ESEM micrographs (a and b) and EDS spectrum (c) from coupon pulled from sampling port C3 (control pipe) on 27 February, Day 9 of the test. Silicon peak in spectrum correlates with diatom colonies on surface. Magnification in (a) is 150X. Size bar at bottom = 100 μm. Magnification in (b) is 300X. Size bar = 50 μm.



(a) (b)



(c)

Figure 11. ESEM micrograph (b) and EDS spectrum (c) from stained area of coupon (a) pulled from sampling port P2 (treated pipe) on 27 February, Day 9 of the test. Brown stains are corrosion products. Magnification in micrograph is 500X. Size bar at bottom = 20 μm.

Discussion

The field experiment described here demonstrated effective, non-chemical biofouling prevention both upstream and downstream of the acoustic source. Specifically, we demonstrated a significant reduction in the rate of micro- and macrofouling, with respect to an untreated control, in a seawater test loop treated with pulsed acoustic waves. Based on viable plate counts, an order of magnitude reduction in bacterial attachment was observed at ranges of at least 10 feet for 0.5-Hz acoustic pulse treatments of less than 4 W/ft^2 for 10 hours per day. Direct observation of treated and untreated surfaces using ESEM revealed substantial reduction of bacterial and algae settlement compared to the untreated control. This effect decreased with time, as organisms that did attach were not removed by the acoustic pulse and continued to grow. Much of the original settlement of microorganisms and algae in the treated pipe presumably occurred at night, when water continued to flow even though the acoustic source was turned off. No degradation of the clear PVC plastic piping was observed.

The most pronounced effects of the acoustic pulse were observed in the segments of piping between the source and the first set of sampling ports, both upstream and downstream. The pipe unions, fittings, sample holders, etc., were not designed in this experiment to be acoustically compatible with the pipe material. Thus, it is almost certain that the acoustic impedance mismatch at these locations resulted in significant dissipation of the acoustic energy traveling through the pipe and the water. This could be confirmed using pressure transducers placed before and after the pipe fittings. On the other hand, when nothing interferes with the acoustic wave, it presumably could propagate for quite some distance. A long cylindrical pipe is an ideal waveguide for this type of energy. These findings suggest that it is the acoustic energy in the pipe that is responsible for preventing settlement of organisms on the pipe surface, rather than the acoustic energy in the water. The implication of this finding is that this technology for biofouling prevention may be best suited for heat exchanger tubes and long piping runs with few flanges, valves or other fittings.

Acoustic and electrical methods for biofouling control have been studied for some time. Conventional ultrasonic sources are the best known of these. The biofouling control mechanism of most ultrasonic devices usually is attributed to the effects of acoustic cavitation. Because of cavitational bubble implosion, extreme temperatures and pressures are generated at the center of the collapsed bubble and free radicals and other highly reactive oxidizing species may be produced [Hua, I., and M. R. Hoffman, 1997].

Our pulsed power method uses *low*-energy acoustic shock waves to prevent, rather than remove, biofouling. Pulsed acoustic shock wave technology differs from conventional sonic and ultrasonic methods in several respects. First, the cavitation threshold is much higher for short-pulse, high frequency (<1 μs duration, >1 MHz carrier) acoustic waves than for low frequency (~10 kHz), continuous wave ultrasonics. The higher cavitation threshold allows more acoustic power to be delivered to the water, at higher efficiency, and lessens the risk of damage to materials and coatings that is associated with cavitation. Secondly, the equipment used to

produce the underwater pulsed shock wave is fundamentally different. Only relatively simple arc-discharge equipment is required.

The biofouling prevention effects that we observed in this test occurred at ranges that exclude the influence of cavitation and ultraviolet illumination. Based on observations of particle movement in the clear pipes, we hypothesize that the mechanism of fouling inhibition involves the interaction of the acoustic pulse with particles (cells) caught in the boundary layers at surfaces in contact with the flowing water column. This interaction reduces the effective "sticking coefficients" of the particles. The mechanism appears to be equally effective in preventing the accumulation of microscopic objects such as bacteria, algae and larvae, as well as macroscopic objects such as sand. Since the effect is non-chemical, but confined to the range of the acoustic wave in the system being treated, it should be more environmentally compatible than competing chemical biocides and thermal treatments alone. Alternatively, experience with other techniques that influence boundary layer diffusion [Costerton, J. W., 1993] makes it likely that biocides used in conjunction with pulsed acoustic treatment will be more effective, especially in low-flow or stagnant regions. Since the focus is on prevention of settlement at the microscopic level, a collateral waste stream essentially is avoided.

Concern is often expressed about using acoustic biofouling control methods on vessels aboard which acoustic signature is a concern. We anticipate that such methods, should they prove useful for shipboard applications, would be used primarily while vessels are in or near port. This represents, in general, the period of highest biofouling risk.

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Appendix A

Patent No. 5,636,180
Inventors: Michael G. Grothaus, Michael S. Mazzola and Marianne Walch
"System for Preventing Biofouling of Surfaces Exposed to Water."

United States Patent [19]

Grothaus et al.

[11] **Patent Number: 5,636,180**

[45] **Date of Patent: Jun. 3, 1997**

[54] **SYSTEM FOR PREVENTING BIOFOULING OF SURFACES EXPOSED TO WATER**

[75] Inventors: **Michael G. Grothaus**, Boerne, Tex.; **Michael S. Mazzola**, Mississippi State, Miss.; **Marianne Walch**, Laural, Md.

[73] Assignee: **The United States of America as represented by the Secretary of the Navy**, Washington, D.C.

[21] Appl. No.: **515,879**

[22] Filed: **Aug. 16, 1995**

[51] **Int. Cl.**[6] **G10K 15/06**

[52] **U.S. Cl.** **367/147**; 367/139

[58] **Field of Search** ..... 367/139, 147; 116/22 A

[56] **References Cited**

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3,486,062	12/1969	Schrom	367/147
4,092,858	6/1978	Edgerton	73/170 A
4,375,991	3/1983	Sachs et al.	134/1
5,208,788	5/1993	Dancer et al.	367/147
5,245,988	9/1993	Einars et al.	367/147
5,397,961	3/1995	Ayers et al.	315/111.21
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Taylor et al. "Ultrasonics as an alternative to Chlorine for inhibiting Biofouling", Johns Hopkins APL Tech. Dig. (USA), vol. 3, No. 3, pp. 295–297. Jul 1982.

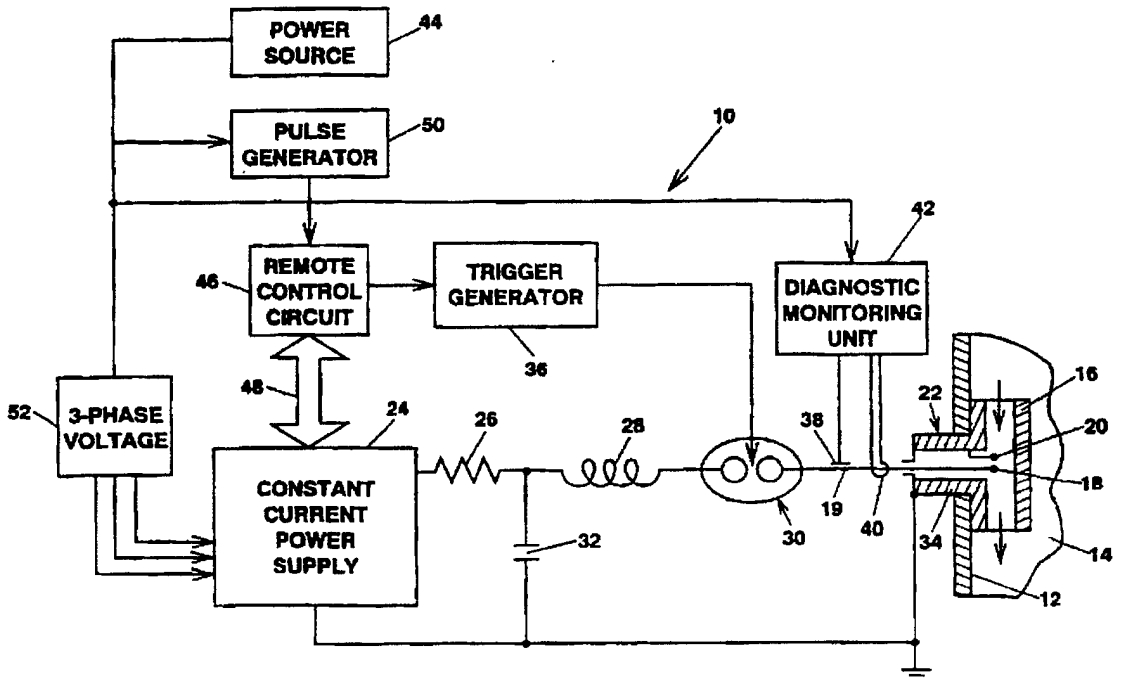
Primary Examiner—Ian J. Lobo

Attorney, Agent, or Firm—John L. Forrest; Jacob Shuster

[57] **ABSTRACT**

Acoustical shock waves are generated by electrical sparks within a gap between electrodes adjustably positioned for exposure to water adjacent a surface immersed therein. High voltage electrical energy derived from a constant current power supply, is stored in a capacitor for rapid, application to the electrodes by discharge during cyclic periods of short duration under remote control in order to render the acoustical shock waves so generated effective in preventing biofouling of the surface by organisms in the water.

7 Claims, 2 Drawing Sheets



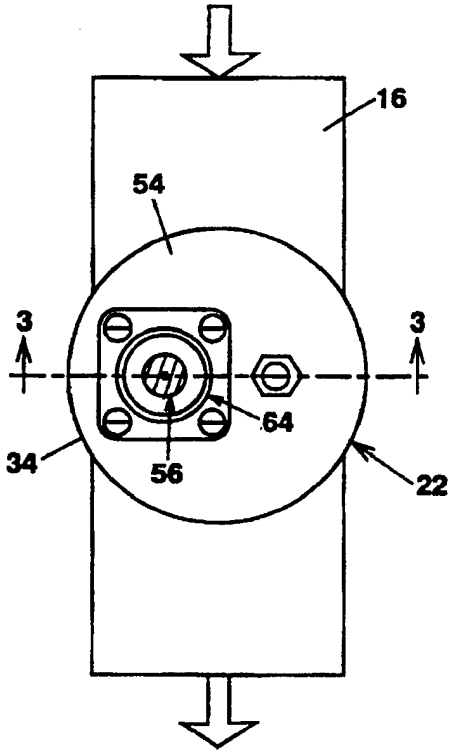

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FIG. 2

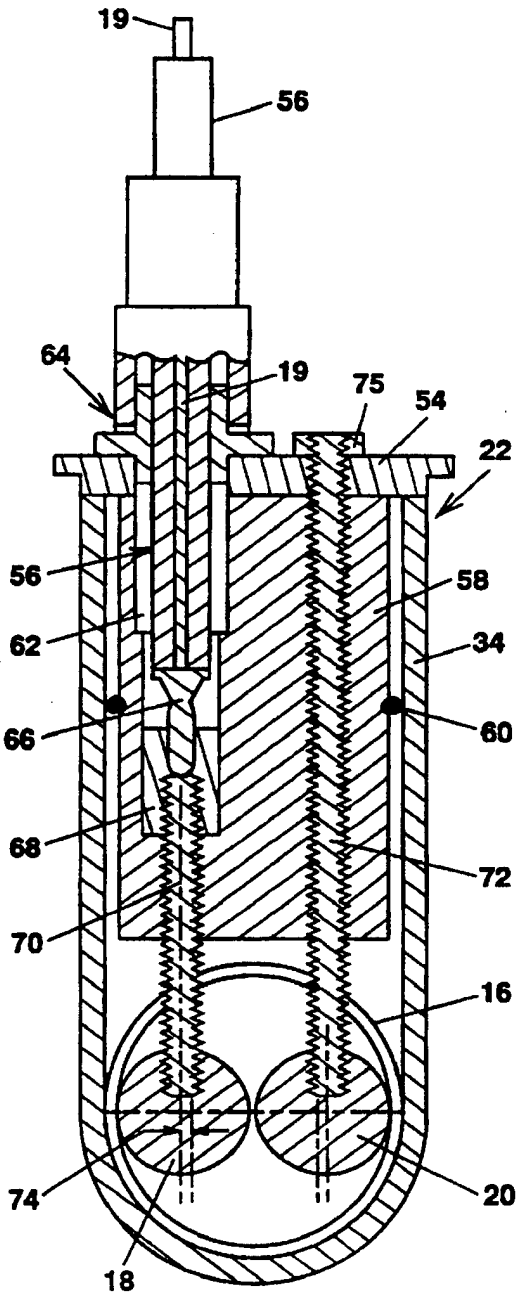
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FIG. 3

SYSTEM FOR PREVENTING BIOFOULING OF SURFACES EXPOSED TO WATER

BACKGROUND OF THE INVENTION

The present invention relates in general to an electrical method and apparatus for preventing biofouling buildup on surfaces exposed to fresh water or saltwater.

The growth and accumulation of biological organisms and the by-products resulting therefrom on surfaces of structures and machinery in contact with either fresh water or salt water, represents a constant maintenance problem for such structures and machinery. For example, the hull of ships and associated seawater exposed systems become coated with both microfouling and macrofouling material such as waterborne algae, bacterial-induced biofilm, barnacles, mussels, etc., which may additionally enhance or induce corrosion.

In order to deal with the foregoing problem, a considerable amount of research activity has been undertaken in an effort to find solutions that are both economical and environmentally compatible, involving various non-chemical treatment technologies including sonics. Biofouling control by use of sonics under study for some time, is now well known and includes the use of conventional ultrasonic sources found to have mixed results for a variety of reasons, including for example a low cavitation threshold at ultrasonic frequencies associated with the use of prior biofouling treating techniques. The use of electric fields and currents in biofouling control applications are also known, but has met with varied results which are furthermore difficult to duplicate.

In connection with the foregoing referred to technologies, U.S. Pat. Nos. 3,486,062, 5,208,788 and 5,245,988 to Schrom, Dancer et al. and Einars et al., respectively, may be of interest. The Schrom patent relates to the generation of shock waves by electric spark discharge from an electrode in a surrounding liquid medium, such shock waves being directed and focused for various types of manufacturing and process operations. The Dancer et al. patent relates to circuitry for triggering sparks within gaps between electrodes for purpose of electrode position detection and correction. As to the Einars et al. patent, it relates to the production of shock waves by electrical discharge of capacitor stored energy between electrodes immersed in liquid for treatment of living tissue. However, none of the foregoing Schrom, Dancer et al. and Einars et al. patents relates to biofouling prevention, treatment or control.

Accordingly, it is an important object of the present invention to generate pulsed acoustic shock waves for continuous biofouling control purposes within a body of liquid water, with greater efficiency in the delivery of acoustic power and having a higher cavitation threshold to enlarge the water treatment region with reduced collateral damage.

SUMMARY OF THE INVENTION

In accordance with the present invention, acoustical shock waves are cyclically produced by high voltage pulses from a storage capacitor across a spark gap between bail-shaped, electrodes adjustably positioned for exposure to water adjacent to a surface immersed therein. Such high voltage pulses, stored within the capacitor during short charging cycles of less than 1 microsecond, are rapidly applied to the electrodes by capacitor discharge through a stray inductance in series with a peaking spark gap device to prevent conduction of current to the electrodes between capacitor charging cycles. Electrical energy for charging of the storage

capacitor during such charging cycles is derived from a constant current power supply that is protected against voltage reversals by a resistor through which the power supply is connected to the storage capacitor. The power supply is also disabled during cyclic periods of capacitor discharge to the electrodes of short duration, under control of circuitry which also controls capacitor charging voltage and charging time. The resulting acoustical shock waves generated at the electrodes, interact with biofouling organisms to prevent attachment thereof to the water immersed surface being protected.

BRIEF DESCRIPTION OF DRAWING FIGURES

A more complete appreciation of the invention and many of its attendant advantages will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawing wherein:

FIG. 1 is a circuit diagram of a biofouling treatment system in accordance with one embodiment of the invention;

FIG. 2 is a top plan view of an acoustic pulse source component of the system depicted in FIG. 1; and

FIG. 3 is a side section view taken substantially through a plane indicated by section line 3—3 in FIG. 2.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENT

Referring now to the drawing in detail, FIG. 1 diagrams a system **10** for preventing biofouling build-up on a wall surface **12** immersed within liquid **14**, such as fresh water or seawater. The liquid in contact with surface **12** is conducted through a pipe section **16** mounted in abutment with surface **12** for exposure of such liquid to pulsed acoustic energy produced by electric sparks in a gap between high voltage electrodes **18** and **20** of an acoustic pulse source generally referred to by reference numeral **22**. At the instant that each spark occurs between electrodes **18** and **20**, a steep compression shock wave is generated which interacts with any bio-matter suspended in the body of liquid **14** within the region adjacent to surface **12** in order to prevent attachment thereof to surface **12**. Such bio-matter includes a variety of organisms. As a result, a significant reduction in the rate of biofouling of an underwater surface by both micro and macro organisms has been achieved in accordance with the present invention.

With continued reference to FIG. 1, the electrode **18** is connected by power line **19** to a constant current power supply **24** through a resistor **26** in series with an inductance **28** and a spark gap peaking type of switch device **30**. A storage capacitor **32** is connected between the power supply and its ground line electrically grounding the electrode **20** through the housing **34** of the acoustic pulse source **22**. Upon closure of the spark gap peaking device **30**, under control of a trigger generator **36**, a high voltage is applied by power supply **24** across the electrodes **18** and **20** through stray inductance **28** and resistor **26** in series therewith. The resistor **26** protects the power supply from voltage reversals without dissipation of any significant amount of power, in view of the constant current nature of the power supply **24**. The voltage and current supplied by discharge of capacitor **32** to the electrode **18** of the acoustic pulse source **22**, are respectively monitored through voltage and current sensors **38** and **40** connected to a diagnostic monitoring unit **42**.

Electrical energy for operation of the monitoring unit **42**, the power supply **24** and the trigger generator **36** is derived

from a suitable power source **44** as diagrammed in FIG. **1**. The power supply **24** is of a commercially available type capable of being externally controlled by a remote control circuit **46** through a 15-pin interface **48**, for example, so as to implement high voltage cyclic charge of storage capacitor **32** through resistor **26**. At the end of each charge cycle, the high voltage power supply **24** is disabled under control of the remote control circuit **46** to isolate the power supply and deliver a signal to trigger generator **36** so as to provide rapid, low energy output pulses causing rapid closure of the aforementioned spark gap peaking device **30**. Rapid application of the high voltage stored in capacitor **32** to the acoustic pulse source **22** through inductance **28**, is thereby achieved. The operating characteristics of the spark gap device **30** may be varied by adjustment of its gap spacing and gas operating pressure, as generally known in the art, to meet desired voltage and current conditions. The voltage and current applied to acoustic pulse source **22** from capacitor **32** are therefore monitored through the aforementioned diagnostic unit **42**. The pulse width of a high voltage pulse of relatively short duration is formed when the switch device **30** discharges capacitor **32** resulting in a discharge current to the electrodes conducted through cable **19** having a rise time of less than one (1) microsecond corresponding to the charging time of capacitor **32** which is controlled by pulse generator **50**. Such charging voltage applied to capacitor **32** under control of pulse generator **50** ranges from 12 to 15 kV, derived from the constant current power supply **24** to which a 208 volt, 3-phase prime power input **52** is fed, as denoted in FIG. **1**. Acoustic waves having a relatively high cavitation threshold is thereby generated at source **22** in accordance with the present invention.

Referring now to FIGS. **2** and **3** in particular, the electrode geometry of the acoustic pulse source **22** is shown enclosed within the housing **34** extending perpendicular from its intersection with the pipe section **16** at which the electrodes **18** and **20** are located. A base plate **54** connected to housing **34** closes its axial end into which the power line **19** extends within a cable., **56**. An insulator body **58** is enclosed within the housing **34** in abutment with the base plate **54**, seating an O-ring **60** in engagement with the housing **34** to form a water-tight seal. The cable **56** extends into a stepped bore **62** formed in the insulator body **58** in alignment with a base plate opening closed by a demountable connector **64** removably anchoring the cable **56** in its illustrated position within the insulator body **58**. The end of the power line **19** within the housing **34** is electrically connected by contact terminal **66** to a conductive adapter plug **68** made of brass, for example. The plug **68** seated in the insulator opening **62** at its lower end, has a threaded bore receiving one end portion of a threaded support rod **70** made of stainless steel. The other end portion of rod **70** below the insulator body **58**, is threadedly connected to the electrode **18** which is in the form of a stainless steel ball bearing, as shown in FIG. **3**.

The other electrode **20** is similar in construction and mounting support to that of electrode **18**, as also shown in FIG. **3**. Thus, a threaded support rod **72** positions the electrode **20** in spaced adjacency to electrode **18**. Such mounting of the ball-shaped electrodes **18** and **20** may be somewhat offset from the axes of rods **70** and **72**, as indicated by reference number **74**, so that spark gap spacing adjustment may be made by either rotating the electrodes on the rods **70** and **72** or replacing them with electrodes having different ball diameters centered relative to the internal diameter of the pipe section **16**. Also, the rod **72** threadedly extends completely through the insulator body **58** between its axial ends, parallel to rod **70**. The upper end of rod **72** furthermore extends through the base plate **54** to which it is anchored by nut **75** and through which the electrode **20** is grounded by connection to the ground line as aforementioned.

From the foregoing description it will be apparent that the pulses generated between the electrodes **18** and **20** of the acoustic pulse source **22** are formed when the spark gap switch **30** causes the capacitor **32** to discharge into the cable **19** to the electrode **18**. The rise time of the resulting current between electrodes **18** and **20** should be less than 1 microsecond as aforementioned corresponding to the limited discharge time of the capacitor **32**. By use of the foregoing described acoustic source **22**, non-chemical treatment to prevent biofouling is achieved both upstream and downstream of its location within an otherwise untreated body of water. Obviously, other modifications and variations of the present invention may be possible in light of the foregoing teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A method of treating a body of liquid within a region in contact with a surface immersed in said liquid, by means of acoustical energy, including generation of the acoustical energy by electrical discharge through a spark gap established within said region, the improvement residing in conducting constant electrical current during charging cycles for cyclic storage of the acoustical energy; preventing conduction of the current to the spark gap during said charging cycles: and limiting said electrical discharge to cyclic periods of short duration of less than a predetermined time to prevent biofouling of the surface.

2. Apparatus for treating a body of liquid adjacent to a surface immersed therein to prevent biofouling of said surface, including: a storage capacitor; an acoustic pulse source operatively connected to the storage capacitor; and means mounting the acoustic pulse source on said surface for cyclic emission of shock waves within the body of liquid in response to discharge of electrical energy from the storage capacitor, the improvement residing in: means operatively connected to the storage capacitor for supplying constant current thereto; and means for controlling storage of the electrical energy by the storage capacitor in response to said supplying of the constant current thereto for limiting said discharge therefrom resulting in current conducted through the acoustic pulse source having a rise time of less than one (1) microsecond.

3. The apparatus as defined in claim **2** wherein the means mounting the acoustic pulse source comprises: a pipe section in abutment with the surface through which the liquid is conducted: a housing extending from the pipe section through said surface in enclosing relation to the electrodes; conductive support means connected to the electrodes for electrical connection thereof to the storage capacitor; and insulator means within the housing through which the conductive support means extends for positioning the electrodes in spaced relation to each other while exposed to the liquid within the pipe section.

4. The apparatus as defined in claim **3** wherein said electrodes are ball shaped.

5. In a system for treating a body of water adjacent to a surface with acoustical shock waves preventing biofouling of the surface, a power supply from which voltage pulses are derived and means for generating said acoustical shock waves comprising: a pair of electrodes: a pipe section through which the water is conducted: a housing connected to the pipe section enclosing the electrodes therein: support

rods connected to the electrodes; insulator means through which the support rods extend within the housing for positioning the electrodes in spaced relation to each other establishing a spark gap; and means operatively connecting the support rods to the power supply for applying said voltage pulses across the spark gap between the electrodes during cyclic periods of short duration to produce said acoustical shock waves within the body of water.

6. The system as defined in claim **5** wherein the means operatively connecting the support rods to the power supply includes: a storage capacitor from which discharge occurs limited to current between the electrodes having a rise time of less than one (1) microsecond corresponding to said cyclic periods of short duration and means limiting charging of the storage capacitor by constant current from the power supply between said cyclic periods of discharge.

7. Apparatus for generating an acoustical shock wave in a liquid medium which comprises:

(a) first and second spaced electrodes contacting the liquid medium.

(b) positioning means for maintaining spacing between the first and second electrodes in contact with the medium adjacent to a surface subject to biofouling;

(c) a pulse-forming network coupled between a power supply and the first and second electrodes for initiating a spark discharge current therebetween; and

(d) output switch means connected between the pulse-forming network and at least one of the electrodes for transmitting a pulse of energy to said electrodes whereby the shock wave is generated in said medium. said pulse-forming network including: at least one storage capacitor within which the pulse energy is stored in response to constant current received from the power supply; and means for limiting said spark discharge current to a rise time of less than one (1) microsecond corresponding to short duration discharge of the pulse energy from the storage capacitor.

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